CHAPTER VIII

ASSURING STRUCTURAL QUALITY

8.1 INTRODUCTION

Control of fabrication quality is important if a suppressive shield is to be constructed with the full strength intended in design. Quality control is exercised by various methods throughout construction. Materials are purchased according to specifications; the construction is performed by certified individuals or companies using qualified procedures; the final product is inspected; and, in some cases, the structure is proof tested.

This chapter contains references to the material and fabrication specifications required to fabricate suppressive shields with full design capability. It includes reference to specific quality control requirements which experience in the suppressive shield design and technology program has indicated are significant factors in shield integrity. Steel and steel fabrication procedures are discussed first, followed by a presentation of considerations applicable to specifications for both standard and fiber reinforced concrete.

8.2 STEEL

8.2.1 Structural Steel

Steel is the most commonly used material in suppressive shields. Structural steels are specified by many organizations and the Federal Government and are categorized for intended use. The American Society for Testing and Materials (ASTM) publishes specifications that cover steels of all strength levels, mill conditions (wrought, forged or cast) and shapes. Other organizations such as the American Institute for Steel Construction (AISC), the American Iron and Steel Institute (AISI), the Society of Automotive Engineers

(SAE), and American Petroleum Institute (API) also specify steels. The API specifications cover piping. In suppressive shield structures, ductility is one of the most important material properties since shields must undergo large deflections beyond the elastic limit without failure. Therefore, the more ductile low carbon structural grade steels are required in this type of structure instead of high strength steels. The structural grade steel ASTM A36 is the most readily available and is the most commonly used.

8.2.2 Reinforcing Steel

Reinforcing bars for use with concrete are specified by ASTM, the Concrete Reinforcing Steel Institute (CRSI), and the American Concrete Institute (ACI). The bars are categorized by strength level and diameter. The CRSI specification provides guidance for the reinforcing steel details such as bending, embedments, splices, etc. Reference 8-1 cites numerous ASTM specifications for reinforcing steel.

8.3 WELDING

8.3.1 General

The requirement for strict quality control of welds became apparent early in the suppressive shield test program when the regular occurrence of weld failures was noted. It was thought at first that the weld failures occurred despite following established welding procedures and that new welding procedures were needed for welds exposed to an explosive environment. However, it was discovered that the occuring weld deficiencies such as undercutting, insufficient fusion, and inadequate joint penetration were the result of not following established welding procedures. It thus becomes apparent in the suppressive shield program that structural integrity is a function of quality control as well as the correct design and analytical procedures.

8.3.2 Welding Processes

Two welding processes are common for field welding applications such as required in suppressive shield construction. Shielded metal-arc welding (SMAW) is the most common process and is used about twice as often as gas metal-arc welding (GMAW). Both processes offer advantages in field applications. The SMAW process is versatile and can be used in all positions with relative ease. The equipment required, power supply, electrode holder and cable, and ground cable are simple to use and field portable. The SMAW process leaves a slag covering on the deposited weld bead which must be removed before the application of another weld bead or paint. GMAW on the other hand provides better quality weld beads with little or no slag covering. The equipment, however, is more cumbersome and less field portable than SMAW equipment. For welding procedures, certified welder requirements, electrode requirements and other information concerning both processes, the AWS Welding Code, AWS D1.1-75, should be consulted.

8.3.3 Welding Defects

In addition to mechanical property changes, especially in the heat affected zone (HAZ), and dimensional defects due to incorrect weld sizes or profiles, improper use of welding procedures as occurred in early suppressive shield construction can introduce defects such as porosity, slag inclusions, incomplete fusion, inadequate joint penetration, undercutting, and cracking into the weld joint. The welding procedures used are governed by the structure being welded, the position of the weld (i.e., flat, overhead, horizontal, or vertical), and the chemical composition of the metal. Carbon levels in the base metal govern the level of preheat temperature used. As a rule, the higher the carbon level, the higher the preheat temperature used. Recommended practices are contained in AWS D1.1-75.

a. Cracking

Cracking is one of the most frequently detected flaws occurring in a weldment (see Fig. 8-1). Cracks occur when the temperature of the cooling weld and base plate is within either of two ranges. One range is at or slightly below the solidification temperature of the weld metal, and the other is from about 400°F to ambient temperature. The high-temperature cracking is called hot tearing and occurs because the metal is weak and has limited plasticity at this temperature. Fillet welds, weld craters, and the heat affected zone (HAZ) display this type of cracking. Low-temperature cracking or cold cracking occurs in root passes of butt welds and in the HAZ. Cracking in this range is invariably associated with the presence of hydrogen as a dissolved impurity.

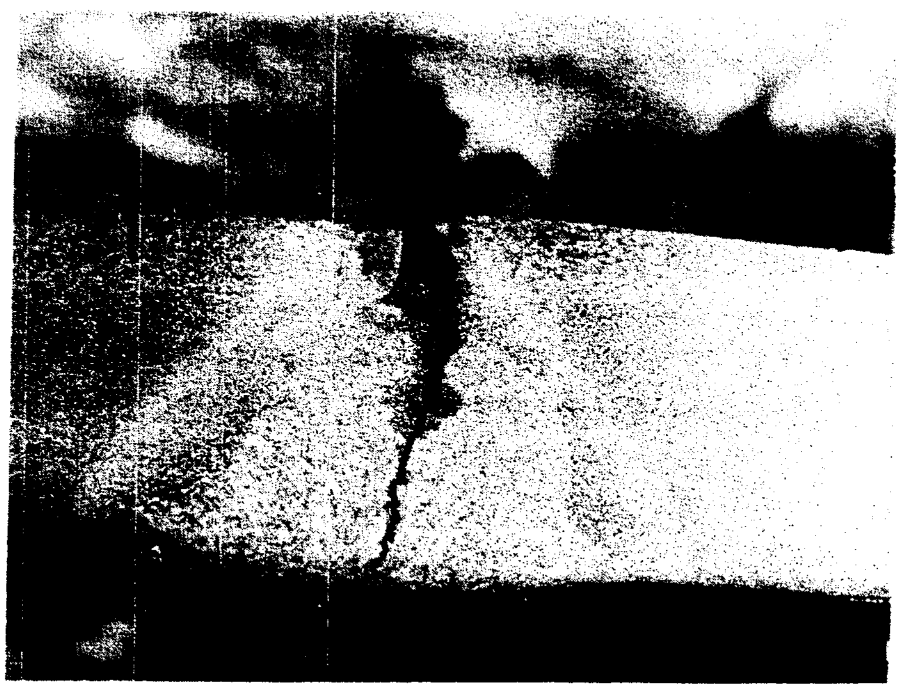

Figure 8-1. Cracking of Weld

(1) Hot Tearing

High-temperature cracks are intercrystalline tears that occur at or near the range of solidification for the metal. They are attributed to low-freezing compounds such as iron sulfide, or solid impurities that have little or no ductility at high temperatures. These tears are located in the metal that is last to freeze. Sulfur contributes significantly to hot tearing, while silicon, phosphorus, carbon, copper, and nickel contribute to a lesser degree. Manganese, on the other hand, has a beneficial effect on hot ductility because it has a greater affinity to sulfur than iron does and forms manganese sulfides. Manganese sulfides have a higher melting temperature than steel and will form globular inclusions rather than the intergranular film that iron sulfide forms. If the ratio of manganese to sulfur in steel is 60 or greater, then hot tearing is not likely to occur. The stresses required to induce hot tearing can be introduced by welding highly restrained joints and by shrinkage due to cooling weld metal and base metal.

(2) Cold Cracking

Cold cracking is induced by the high stresses resulting from the cooling weld metal. When the weld cools, the metal contracts and tends to get smaller in length, width, and height. This contraction puts the weld metal into tension because the shortening and lateral contraction are resisted by the surrounding colder base metal. The resulting tensile stresses can cause plastic deformation of the weld, especially at higher temperatures when the metal is weak. When the temperature reaches the transformation range, the metal becomes stronger but less plastic. Below the transformation range, the plastic flow is similar to cold working, which tends to use up the ductility of the metal.

Since most mild steels are susceptible to strain aging effects in the temperature range below 1000°F, which causes them to lose ductility quickly when cold worked, the danger of cracking rises continuously as the metal cools to room temperature. If there is a notch of some type present, such as the root of the joint, it will act as a stress riser and will also inhibit plastic flow.

As previously mentioned, hydrogen is a contributing factor in cold cracking. There are three factors acting simultaneously in the generation of hydrogen-induced cracking: dissolved hydrogen, tensile stresses, and a low-ductility microstructure such as martensite. The source of hydrogen is the shield gas, flux, or surface contamination. The hydrogen is carried to the arc and converted to the atomic or ionized state, which readily dissolves in the weld metal. As the weld metal cools, it becomes super-saturated and the hydrogen diffuses to the HAZ and the atmosphere. Under rapid cooling conditions, when the steel transforms to martensite, the hydrogen becomes trapped. Since hydrogen has a very low solubility in the martensite structure, it is at a very high energy level and seeks discontinuities in the microstructure where it can decrease its energy levels. The hydrogen concentrates in these discontinuities and, in conjunction with external stresses, enlarges them to crack size.

Joint design and attention to joint fit-up can reduce the chances of cold cracking. To reduce the tendency toward hydrogen-induced cracking, a post-weld temperature of 400°F for up to 10 hours (depending on weld thickness) is recommended. Joint cleaning and the use of low hydrogen electrodes are also recommended to limit the source of hydrogen.

b. Porosity

The AWS defines porosity as cavity type discontinuities formed by gas entrapment during solidification (see Fig. 8-2). The gases that form porosity are either driven from solution because of low solubility at lower temperature or are produced by chemical reactions in the molten weld puddle. These gases are trapped in the weld metal because there is insufficient time to rise to the surface of the puddle before solidification occurs. The formation of porosity can be avoided by not using excessively high currents or long arc lengths. This is especially true for shielded metal-arc welding (SMAW) because high currents and long arc lengths will consume large amounts of deoxidants in the electrode covering, leaving little to combine with excess gases in the weld pool. The distribution of porosity will give some indication of the cause.

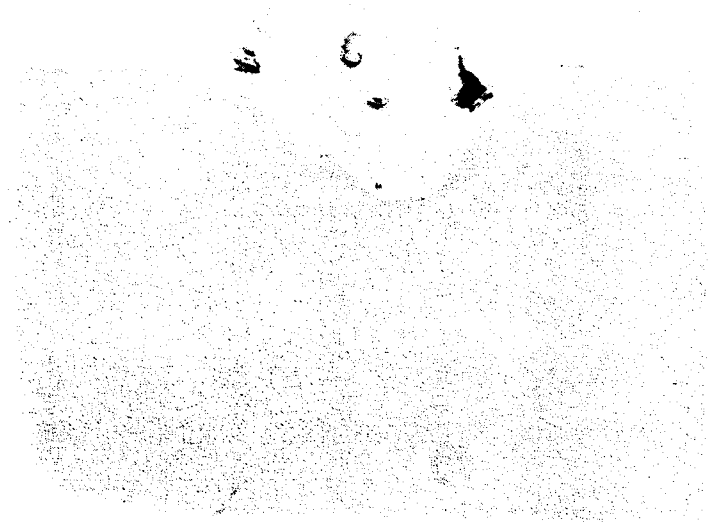

Figure 8-2. Porosity in Weld

Uniformly scattered porosity can be found in many weldments and is of little concern, because there are usually large distances of sound metal between the pores. Clustered porosity is often associated with changes in arc conditions. Starting and stopping areas frequently contain clustered porosity. Linear porosity is usually found in the root pass and is considered a special case of inadequate joint penetration.

c. Incomplete Fusion

Incomplete fusion is the condition in which two weld beads have not fused together or the base metal and a weld bead have not fused (see Fig. 8-3). Incomplete fusion is caused by failure to raise the adjoining material to the fusion temperature or failure to dissolve any oxides or other foreign material on the surface that the new weld bead must fuse to. Incomplete fusion can be avoided by proper cleaning of the weld joint before depositing a new bead and by proper use of welding procedures.

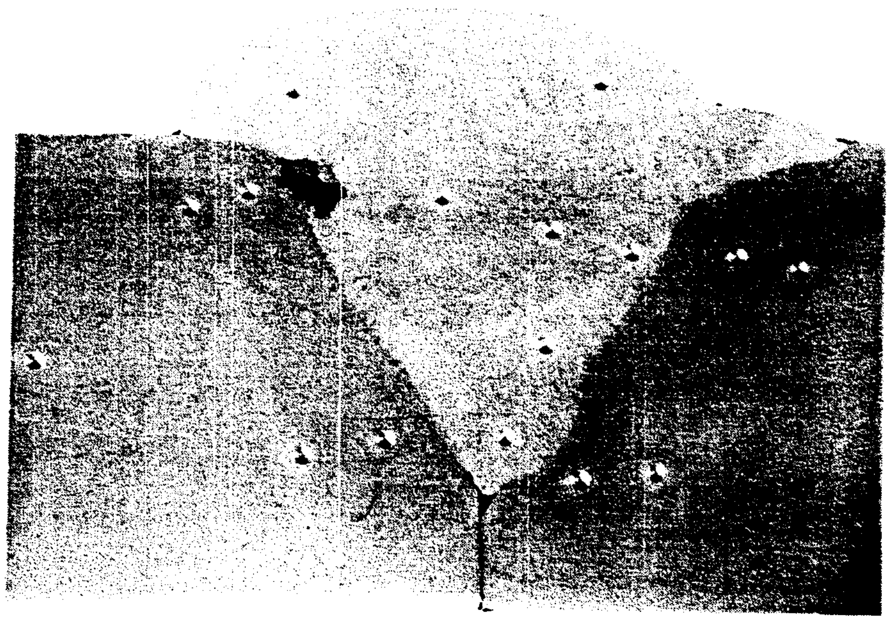

Figure 8-3. Incomplete Fusion at Sidewall and Incomplete Joint Penetration at Root

d. Inadequate Joint Penetrations

Inadequate joint penetration is the condition in which fusion of the weld and base metal at the root of the joint is less than specified by design (see Figs. 8-3 and 8-4). Although the cause may be a poorly cleaned joint, it is more often heat transfer conditions in the joint that cause inadequate penetration. Heat transfer can be increased by using wider angles for V-grooves or using a root opening. Poor penetration is detrimental to weld joints that will be stressed in service because the root forms a notch that acts as a stress concentrator, which leads to an early failure of the joint.

Figure 8-4. Undercut Weld and Incomplete Penetration at Root

e. Undercutting

Undercutting refers to either a sharp recess in the sidewall of a weld joint or the reduction in thickness of the base plate at the toe of the last weld bead on the surface of the plate (see Fig. 8-4). In both cases, the primary cause of undercutting is the welder's technique. High currents or high voltage, as well as low current and fast travel speeds, may increase the tendency to undercut. If the undercutting is a sharp recess in the joint sidewall, it should be smoothed out by grinding or chipping. The surface undercut can easily be detected. The AWS Welding Code has limitations for undercutting.

f. Slag Inclusions

Slag inclusions are oxides or nonmetallic solids that become trapped in the solidifying weld metal. The inclusions can be either completely surrounded by weld metal or be between the weld metal and the base plate. In the SMAW process, chemical reactions between the weld metal and coating materials produce a nonmetallic slag that has low solubility in the weld metal and generally will float to the surface. In some instances, the slag is forced into the weld metal by the stirring action of the arc, or flows ahead of the arc and is covered by the weld metal. Slag inclusions can be prevented by proper cleaning and preparation of the weld joint, by using good technique, or by increasing the heat input and preheat to make the weld metal less viscous and slow the solidification rate. Increasing the heat input provides more energy to melt the slag and the metal and gives the slag more time to float to the surface.

8.3.4 Weld Inspection Methods

A family of methods for investigating the quality, integrity, and dimensions of materials and components without damaging or impairing their serviceability is called nondestructive testing. Any of the following methods may be used in the fabrication of Suppressive Shields.

a. Visual Methods

Visual inspection is always required in weld inspection. Although visual inspection of a weld is the quickest, easiest and cheapest method, internal defects and minute surface defects cannot be detected. The specified size of a weld can be rapidly checked visually by using a welding gage to measure the dimensions of the weld metal. Visual inspection may be the only type of inspection required for welds which are designed primarily to hold parts together and are not significantly stressed in service. A more efficient method is required if survivability of the structure depends upon the integrity of the weldment.

b. <u>Penetrant Inspection Method</u>

Penetrant inspection is a nondestructive test for discontinuities open to the surface in parts of nonporous materials. This is done by treating the whole area with a fluid which penetrates into the surface discontinuity by capillary action. The surplus penetrant not in the discontinuity is removed. The penetrant remaining in the discontinuity is returned to the surface by an absorbant developer. It is a quick and positive method for detecting many different types of surface discontinuities.

c. <u>Magnetic Particle Inspection Method</u>

Magnetic particle inspection is a rapid nondestructive means of detecting discontinuities in materials having ferromagnetic properties, principally iron and steel. Magnetic particle inspection is accomplished by inducing a magnetic field into a part. A defect will interrupt this field creating new north and south poles with the magnetic flux bridging the defect. This flux leaking attracts the magnetic particles to form the indication. In addition to cracks, the types of flaws that can be detected by an experienced observer include seams, laps, folds, and nonmetallic inclusions that are either surface or slightly subsurface.

d. <u>Ultrasonic Inspection Method</u>

Ultrasonic inspection is a method of inspection using sound waves above the audible range. High frequency sound is induced into the part by a transducer. This ultrasonic energy travels through the part. Any marked changes in acoustic properties (flaws, interface or back surface) will reflect the sound back to the transducer while a weld without defects will not impede passage of the sound waves. This information is normally displayed on an oscilloscope. Proper selection of transducer, frequency, sensitivity, angle, etc., will enable inspection of the surface, subsurface, and back surface of the part.

e. Radiographic Inspection Method

Radiographic inspection is a nondestructive inspection method utilizing a source of X-rays or gamma rays to detect discontinuities in materials and components. X-rays penetrate metallics and nonmetallics and are differentially absorbed. Discontinuities, which are less dense than metal absorb less radiation and thus are shown on the recording medium as dark shadows. The recording medium is usually film, but it can be any means that converts radiation energy into a visible image. Radiography is used to inspect both metallic and nonmetallic materials. It has the capability of inspecting the interior of opaque objects or assemblies without access to the inside. This method is expensive to use but very reliable and provides a permanent record of the weld quality. Special precautions must be taken to contain the hazardous radiation that is emitted.

8.3.5 Weld Repairs

Repairability of defective welds is probably one of weldings greatest virtues. The quality of a welded structure must be insured by producing sound welds, but flaws in the initial placement of welds are readily repaired as long as adequate inspection methods are used for detection. There is a limit to the amount of weld repair that is advisable in lieu of rejecting a part. Generally, the amount of weld repairs can be quite extensive without affecting the strength of the joint. This is possible because the repair process involves removing the defect by grinding, chipping, cutting, gas gouging, etc., to expose clean sound surfaces and then replacing the removed material with new weld metal. The metal is, therefore, joined together by weld metal which develops the full strength and cross sectional area of the structural members. Often the appearance of the repaired section is such that it cannot readily be distinguished from the original material.

8.4 CONCRETE

8.4.1 General

Concrete is a much more variable construction material than steel and its final properties are much more dependent on its constituents and methods of mixing, placing and curing. Hydraulic cements are used almost exclusively for the manufacture of structural concrete and the most common type used is portland cement. Concrete tensile strength is very low compared to its compressive strength and, therefore, it is always combined with steel reinforcing in suppressive shield applications. Quality assurance requires close inspection at all stages of mixing, placing and curing. This would reduce the problem of voids, a problem in some suppressive shield foundations.

8.4.2 Mixing

Quality control in the mixing operations must begin with the selection of materials. Cements, aggregate admixtures and mixing water must meet the standard specifications of the American Society for Testing Materials. Reference 8-1 contains a list of the applicable specifications. Mixture designs can be obtained using standard procedures and should be verified by a suitable test program.

The cement-water ratio is the chief factor controlling the strength of concrete. It also affects the workability of the concrete and an inspector must be vigilant to prevent the addition of water to a mix to improve its workability at the expense of its compressive strength. Once a mix design has been developed, the slump test provides a reasonably quick field check on quality control.

The principal purpose of mixing is to produce an intimate mixture of cement, water, fine and coarse aggregate. This is achieved in machine mixers of the revolving-drum type. Minimum mixing time is 1.5 minutes. Mixing can be continued for a considerable time without adverse effect. This fact is particularly important in connection with ready-mixed concrete.

On large projects, where ample space is available, mixing plants are installed and operated at the site. On smaller jobs, ready-mixed concrete is used. Such concrete is batched in a stationary plant and then hauled to the site in trucks in various ways. The most common method is transit-mixed, i.e., batched at the plant but mixed in a truck mixer. Concrete should be discharged from the mixer or agitator within at most one and a half hours after the water is added to the batch.

8.4.3 Placing

Most structural concrete is carried from the mixer or truck to the form in wheelbarrows or buggies or by pumping through pipelines. The chief danger during conveying is that of segregation. The individual components of concrete tend to segregate because of their dissimilarity. In overly wet concrete standing in containers or forms, the heavier gravel components tend to settle, and the lighter materials, particularly water, tend to rise. Lateral movement within the forms tends to separate the coarse gravel from the finer components of the mix. The danger of segregation has caused the discarding of some previously common means of conveying, such as chutes and conveyor belts, in favor of methods which minimize this tendency.

Prior to placing, loose rust must be removed from reinforcement, forms must be cleaned, and hardened surfaces of previous concrete lifts must be cleaned and treated appropriately. Proper placement must avoid segregation, displacement of forms or of reinforcement in the forms, and poor bond between successive layers of concrete. Immediately upon placing, the concrete should be compacted by means of hand tools or vibrators. Such compacting prevents honeycombing, assures close contact with forms and reinforcement, and serves as a partial remedy to possible prior segregation. Compacting is achieved most commonly with high-frequency, power-driven vibrators. These are of the internal type, immersed in the concrete, or of the external type, attached to the forms. The former are preferable, but must be supplemented by the latter where narrow forms or other obstacles make immersion impossible.

8.4.4 Curing

Fresh concrete gains strength most rapidly during the first few days and weeks. Structural design is generally based on the 28-day strength, about 70 percent of which is reached at the end of the first week after placing. The final concrete strength depends greatly on the conditions of moisture and temperature during this initial period. Thirty per cent or more of the strength can be lost by premature drying out of the concrete; similar amounts may be lost by permitting the concrete temperature to drop to 40°F or lower during the first few days, unless the concrete is maintained continuously moist for a long time thereafter. Freezing of fresh concrete may reduce its strength by as much as 50 percent.

Concrete should be protected from loss of moisture for at least 7 days and, in more sensitive work, up to 14 days. When high-early-strength cements are used, curing periods can be reduced. Curing can be achieved by keeping exposed surfaces continually wet through sprinkling, ponding, covering with wet burlap, or the like. Sealing compounds, when properly used, form evaporation-retarding membranes. In addition to improved strength, proper moist curing provides better shrinkage control. To protect the concrete against low temperature during cold weather, the mixing water and, occasionally, the aggregates are heated. Temperature insulation is used where possible and when air temperatures are very low, external heat may have to be supplied in addition to insulation.

8.4.5 Quality Control

Because of the variability in the properties of concrete, a systematic quality control program must be instituted at the construction site. The primary measure of the structural quality of concrete is its compression strength. Tests for this property are made on cylindrical specimens prepared in accordance with ASTM C172, Method of Sampling Fresh Concrete, and ASTM C31, Method of Making and Curing Concrete Specimens in the Field. The cylinders are moist-cured, generally for 28 days, and then tested in the laboratory at a specified rate of loading. The compression strength obtained from such tests is known as the unconfined compressive strength, f'_c and is the main property specified for design purposes.

Inspection during construction should be carried out by a competent engineer, preferably the one who produced the design or one who is responsible to the design engineer. The inspector's main functions in regard to materials quality control are sampling, examination, and field testing of materials, control of concrete proportioning, inspection of batching, mixing, conveying, placing, compacting, and curing, and supervision of preparation of specimens for laboratory tests. In addition, he must inspect formwork, placing of reinforcing steel, and other embedded items. Deficiencies in these items are impossible to detect after placement of concrete. The importance of thorough inspection to the correctness and adequate quality of the finished structure cannot be emphasized too strongly.

8.5 FIBER REINFORCED CONCRETE

The low tensile strength and brittle character of conventional concrete can be improved by the addition of metallic, organic or inorganic fibers. Several investigators have found that the energy absorption capacity of fiber reinforced concrete is at least an order of magnitude higher than that of plain concrete (Ref. 8-2). Studies and tests have indicated that randomly distributed fibers in concrete increase considerably the spalling and shatter resistance of concrete members which are subjected to explosive loadings such as those of suppressive shields. Steel fibers, up to about 4 percent by volume, were found to increase the first crack flexural strength of concrete up to 2.5 times that of the unreinforced materials and slightly improve the compressive strength. The steel fibers used in concrete have lengths ranging from 0.25 to 3 inches. The round fibers have diameters between 6 and 30 mils. Flat steel fibers have cross sections ranging from 6 to 16 mils in thickness by 10 to 35 mils in width.

Although the fibers can enhance the properties of concrete, they can present problems in mixing and placement. Fibrous concrete requires a considerably greater amount of fine material than does plain concrete to achieve the same degree of workability. Reference 8-2 discusses some alternate techniques for adjusting workability.

The addition of steel fibers to concrete greatly influences its mixing characteristics. Each piece of mixing equipment has its own operating characteristics and will require a procedure tailor-made for the type of equipment to be used. The equipment should be checked out if it has not been previously used to mix fibrous concrete. Excess mixing has a tendency to develop fiber balls in certain types of mixers, and, generally, additional mixing will not break up the balls. To alleviate this problem, the fibers may be dispersed in and among the coarse aggregate prior to the addition of the fine aggregate, cement, and water.

The aspect ratio (ratio of fiber diameter or width to length) also affects the tendency toward balling. The higher the ratio, the more likely balling will occur. If balling occurs, the fiber balls should be picked out before they reach the forms. The addition of fibers decreases the mobility of concrete mixes, and problems with consolidation can occur if the spacing between the reinforcing bars is too small. The time to consolidate the concrete increases drastically when the bar spacing is less than twice the length of the fibers.

Fiber reinforced concrete was utilized in the Group 3 Suppressive Shield roof and foundation with great success. The use of fiber reinforced concrete in all new suppressive shield construction is highly recommended as an additional safety precaution.

8.6 REFERENCES

8-1 Building Code Requirements for Reinforced Concrete, ACI Standard 318-71, American Concrete Institute, Detroit, Mich., 1971. (U)

8-2 Gray, B.H., Williamson, G.R., and Batson, G.B., Fibrous Concrete Construction Material for the Seventies, Construction Engineering Research Laboratory, Champaign, Ill., May 1972. (U)